

MODELLING THE PHASE-LOCKED PULSATIONS OF A P=14d EROS STAR

Z. KOLLÁTH^{1,2}, J.R. BUCHLER¹, J.P. BEAULIEU^{3,4}, M.J. GOUPIL⁵

¹ *Physics department, University of Florida, Gainesville, FL 32611, USA.*

² *Konkoly Observatory, 1025 Budapest, Box 67, Hungary.*

³ *Institut d'Astrophysique de Paris, CNRS, 98bis Boulevard Arago, F-75014 Paris, France.*

⁴ *Kapteyn Laboratorium, Postbus 800, 9700 AV Groningen, The Netherlands.*

⁵ *DASGAL, Observatoire de Paris, Meudon 92195, France.*

Abstract

The Fourier spectral analysis [1] of this object suggests a nonlinear pulsation of period ≈ 14 d with a 3:2 frequency lock between two vibrational modes. We discuss an extensive search that we have performed in the L, M, T_{eff} space for models of period 14–16 days that exhibit this particular resonance. We find models satisfying the resonance constraints both in the Cepheid and in the post AGB regimes. The nonlinear pulsations of several candidates are presented. The nature of the star remains a mystery as none of the models satisfies all the observational constraints.

1 Linear models

We have performed an extensive search of linear nonadiabatic radial models with periods of $P=14$ –16 days. We have chosen this value because nonlinear and nonadiabatic effects tend to reduce the period somewhat, but the results are insensitive to the exact value of the period.

The hydrostatic models and their linear stability analyses are computed for composition parameters $X=0.35$ –0.90, each with $Z=0.004$, $Z=0.01$ and $Z=0.02$. The OPAL [2] and Alexander & Ferguson [3] low temperature opacities are used. Convection is ignored. For a fixed value of the temperature and the luminosity we iterate the mass to get the desired pulsation period of ≈ 15 days for the fundamental mode or for the first overtone. Repeating this procedure for different values of T and L we obtain the period ratio (P_1/P_0 or P_2/P_1) as a function of these two parameters.

We present the results for $X=0.7$ and $Z=0.01$ in Figure 1. Each curve has a fixed luminosity ($L=2,000L_\odot$ for the most left and $L=12,000L_\odot$ for the most right curve). The mass decreases from the left to the right in each sequence. The highest mass is between 3 and 6 M_\odot , on the right side, the calculations on the blue side of the sequences are terminated for masses 0.3 and 0.6 M_\odot when we encounter numerical problems due to the high luminosity to mass ratio. The dots represent the unstable (fundamental mode) models. Two groups of unstable stars are found. The first group around $T_{eff}=5,000$ K is inside the Cepheid instability strip while the second one gives the region for the unstable post-AGB stars (for a general linear survey of PAGB stars see eg [5]).

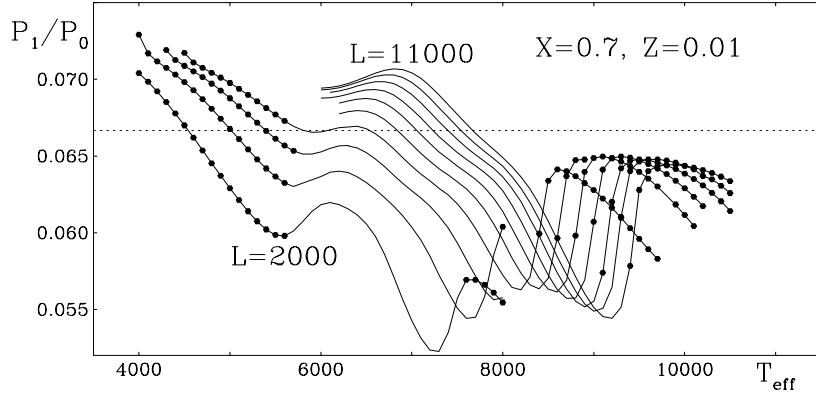


FIG. 1. First overtone to fundamental mode period ratio as a function of temperature, luminosity ranging from 2000 to $11000L_{\odot}$; dots denote linearly unstable models; on the left is the Cepheid group, on the right the PAGB group.

Models with a 3:2 period ratio exist only among the Cepheids ($L=2,000\text{--}4,000L_{\odot}$) for this composition of $X=0.70$, $Z=0.01$. However the observations [1] indicate a higher temperature and a higher luminosity for this star than our search for these model parameters yield.

Interestingly, the period ratio increases close to the 3:2 resonance, right where the instability occurs in the second, PAGB group. The ratio P_1/P_0 reaches the highest value around $T_{eff}=9,000$ K which, however, is still lower than the spectroscopic estimate.

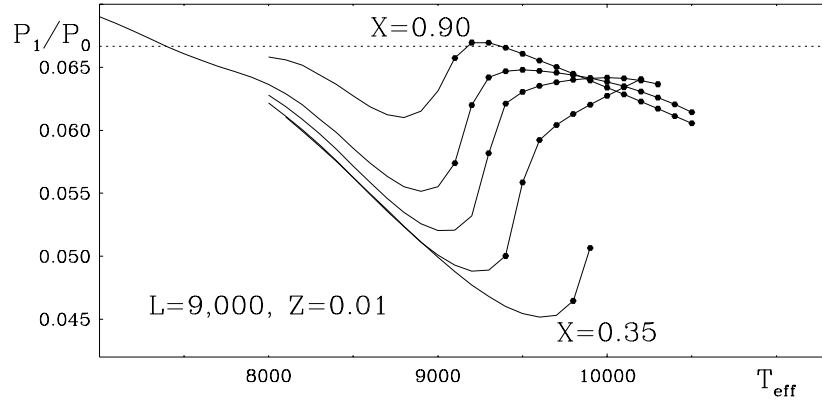


FIG. 2. Period ratio (P_1/P_0) as a function of temperature for different values of the hydrogen content (X).

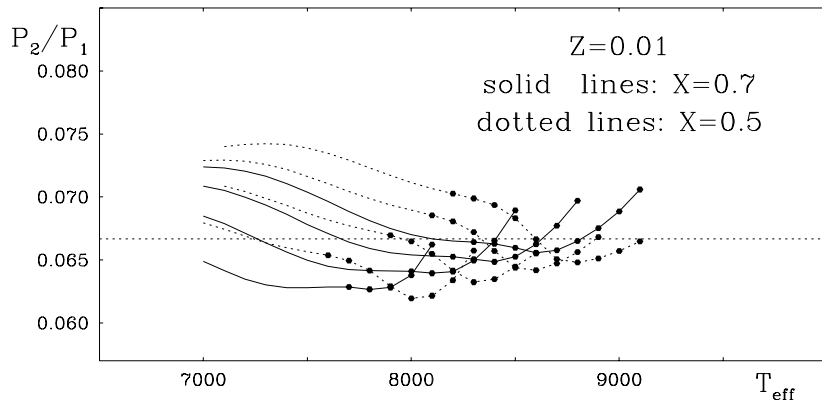


FIG. 3. Period ratio (P_2/P_1) as a function of temperature. $L = 7000, 9000, 10000$ and $13000 L_{\odot}$ (left to right).

The dependence of the period ratio on the composition is illustrated in Figure 2. Here we present only the high temperature models for $L=9,000L_{\odot}$. The curves are given for the composition of $X=0.9$ (top), 0.7, 0.6, 0.5 and 0.35 (bottom) with $Z=0.01$. There is a clear increase of the maximum value of the period ratio as the hydrogen content is enhanced. An increase to $X=0.9$ gives the right period ratio, but this is an unacceptably large X , especially since we are in the PAGB region. For $X=0.5$ the period ratio is still increasing at the blue end of the curve but both the mass and the linear growth rate become small.

We have also performed tests with different values of metallicity. Different values of Z only bring about a small shift of the curves. We cannot push up the period ratio to reach the resonance by varying the metallicity in the case of normal X values.

We now turn to first overtone pulsators. Here, there now also are solutions for the $P_2/P_1=2/3$ resonance for lower values of X . The period ratio as the function of the effective temperature is displayed on Figure 3. The curves are given for $L=7000, 9000, 11000$ and $13000L_{\odot}$ and for $X=0.5$ (dotted lines) and $X=0.7$ (solid lines). The resonance occurs in the range $T_{eff}=8000-9000$ K. The loci of the resonance are slightly shifted to the higher temperatures for the $X=0.5$ case compared to the higher X models.

2 Nonlinear models

From the Cepheid instability strip we have selected a resonant model with the following parameters: $M=3.8M_{\odot}$, $L=3081L_{\odot}$, $T_{eff}=5156$ K, $X=0.7$ and $Z=0.01$ with $P_0=14.1$ d. The numerical hydrodynamics shows that the resonance does indeed lead to a phase-lock with alternating cycles (*cf* [4] for an explanation of this phenomenon). The theoretical velocity and light curve are displayed on Figure 4. The light variation shows similar alternations as the EROS star, and the Fourier amplitude spectrum is very similar to the observed one. The amplitude of the variation (≈ 1.8 mag) is however much higher than the observed value (≈ 0.5 mag). These differences are perhaps not astonishing since both the temperature and luminosity of the model are much lower than the observationally estimated values of the star.

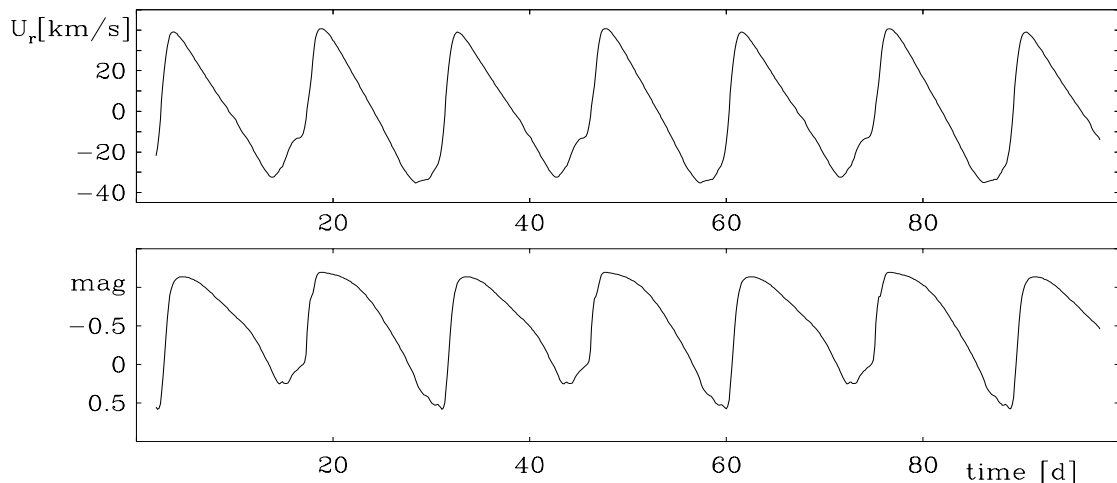


FIG. 4. Variation of the Cepheid model. Velocity (top) and light curve (bottom).

We have also calculated nonlinear models of the PAGB stars close to the linear resonance. In general we find that the computed amplitudes of these models are very small (usually between 0.001–0.010 mag.) in agreement with calculations of PAGB models [6], but in disagreement with the observed value for this star. In contrast to the Cepheid model the growth rates are very large and the models tend to undergo irregular (chaotic) pulsations.

One of the few models for which the linear frequencies satisfy closely the resonance criterion has the following parameters: $M=1.1406M_{\odot}$, $L=9566L_{\odot}$, $T_{eff}=9300$ K, $X=0.9$ and $Z=0.01$. For this model both the fundamental mode and the first overtone are linearly unstable (with the growth rates of $\eta_0=0.36$ and $\eta_1=0.37$). However, for none of the PAGB models have we found any alternations similar to the observations.

As far as overtone pulsators are concerned the linear results have indicated that the P_2 to P_1 resonance provides good candidates for modelling this unique star. However, the fundamental mode is also unstable, and all of our nonlinear models (initialized with the first overtone velocity eigenvector) converge to the fundamental mode pulsation after a short transient.

3 Conclusion

The nature of the $P=14$ d phase locked star remains a mystery in spite of a thorough search with radiative linear and nonlinear stellar models. The linear study shows that both Cepheid models and PAGB models have the right period ratio between the fundamental mode and first overtone. However, all of the Cepheid models are underluminous and too cold compared to the observations. Furthermore, numerical hydro computations show that the pulsation amplitudes for these models are too high. For PAGB models the resonance does not occur with reasonable composition parameters for the fundamental mode, but can occur for first overtone pulsators. However, our hydrodynamics models are not able to reproduce the observed alternations in the pulsations. The theoretical light curves of the high luminosity and high temperature models also have very low amplitudes contrary to the observations.

It is important to get further observational confirmation and a better estimation of the parameters of this unique variable star, because the modelling can be an important test for our understanding of the physics inside this kind of stars.

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References

- [1] Beaulieu, J.P. et al., 1996. this volume
- [2] Iglesias, C. A. & Rogers, F. J., 1996. *Astrophys. J.* **464**, 943
- [3] Alexander, D. R. & Ferguson, J. W. 1994. *Astrophys. J.* **437**, 879
- [4] Moskalik, P. & Buchler, J. R. 1990, *Astrophys. J.* 355, 590
- [5] Gautschi, A., 1993. *Mon. Not. R. astr. Soc* **265**, 340
- [6] Zalewski, J., 1993. *Acta Astr.* **43**, 431